

Chapter 3

Power Supplies

More power!...Tim Allen

So how does the power supply work? The acronym SCR (silicon controlled rectifier) is heard quite often in the MCR and it is a vital component to a power supply. The SCRs are semiconductors that behave like diodes except that they can be gated on. Diodes, when forward biased, conduct until the voltage drop across it is zero volts. For an SCR, it can conduct when it is forward biased but only after receiving a gate pulse. This allows control over how much of a sine wave will pass through the SCR. Refer to the diagram below.

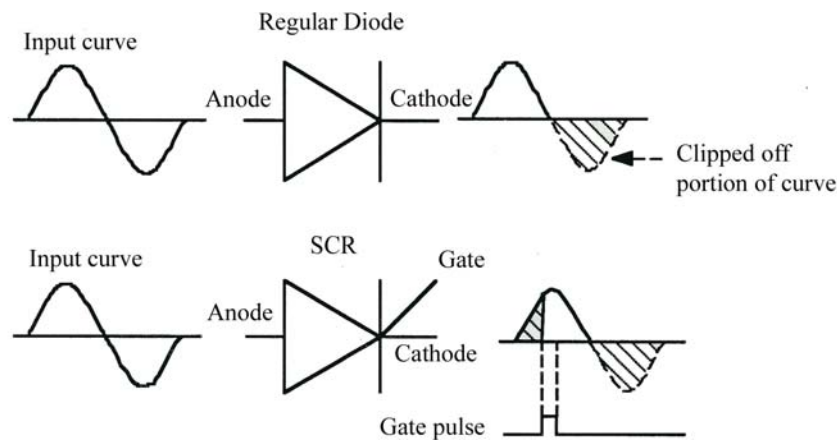


Figure 3.1. Diagram showing the difference between a diode and SCR.

In a Tevatron power supply, the input from the utility yard is in the form of 4 conductors each coming from the X and Y transformer secondary side. These inputs go to 2 banks of SCR modules that are coupled together. Each module contains 4 pairs of SCRs; one pair connected to each leg of the Wye transformer and one bypass SCR connected to the neutral terminal of the transformer. This configuration results in a 12 phase fullwave rectification.

A 12 phase system is employed so that the resulting ripple at 720 Hz can be easily filtered out. The filtering is accomplished with a 0.8 mH choke (inductor) located next to the supply. The harmonic filtering network is located in the dump/filter cabinet.

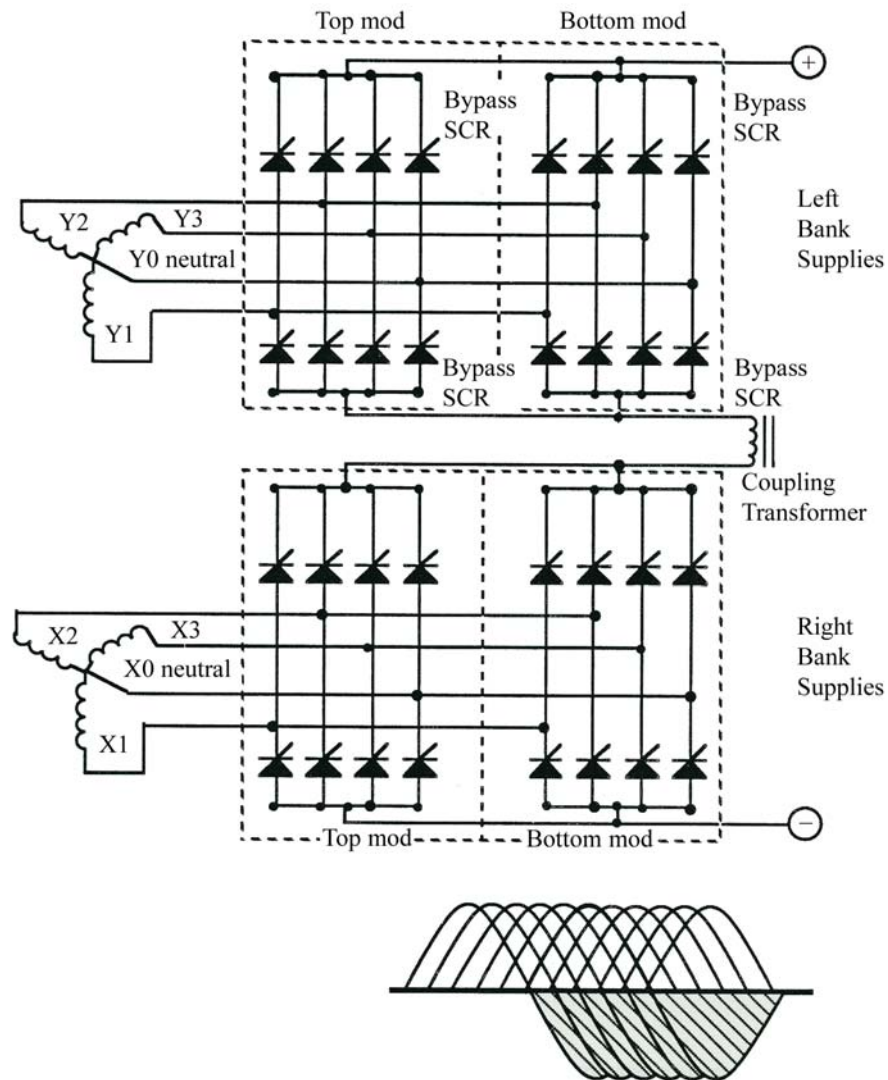


Figure 3.2 Power supply schematic.

The power supplies are turned on (or commutated) by providing a firing voltage to the gates of the SCRs in the SCR modules. Each SCR requires 14 V to conduct and that is supplied by the CVT (constant voltage transformer), located in the electronics rooms behind the racks. The CVT voltage itself is gated by the SCR Unit, which gets inputs from the PT (potential transformer) in the yard and TECAR. TECAR determines the firing angle of the individual SCRs and sends the command to commute, which, in turn, determines the output of the power supply.

The PT is a 13.8 kV to 120 V transformer located inside the 13.8 kV cubicle. Its purpose is to provide a phase reference for the SCR Unit by knowing the incoming 13.8 kV phase.

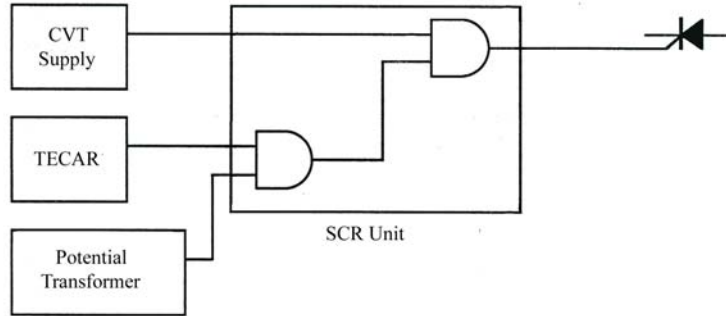


Figure 3.3 SCR Unit inputs.

The 774 dipoles, 216 quadrupoles, and 12 power supplies form a single series circuit with “upper” and “lower” busses connected at a “fold” in the B0 straight section. All of the power supplies are capable of ramping to 4500 A at 1 kV. Eleven power supplies operate in a voltage regulation mode to ramp the current up and down. The A2 power supply acts as the current regulator and the A3 power supply is its back up. Since the resistance of the entire Tevatron circuit is small, the current regulator can provide the required voltage during flattop. Only this supply must be capable of conducting continuous flattop current. Collider mode requires 6 power supplies with the remainder held in reserve.

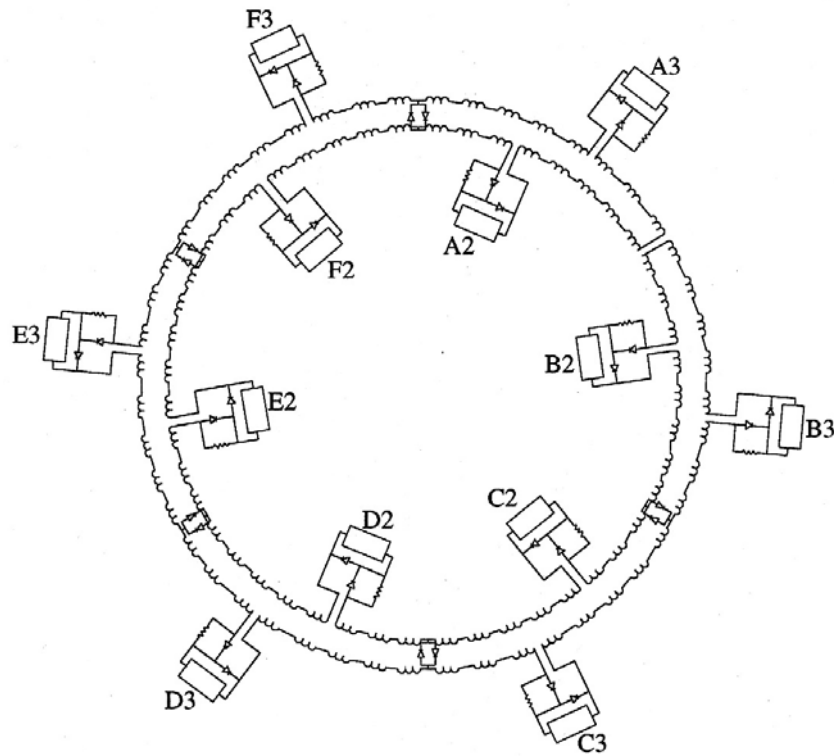


Figure 3.4 Tevatron power supply distribution around the ring.

The TeV power supplies are distributed around the ring at each of the “2” and “3” houses. Each power supply circuit consists of a DC breaker, series SCR, dump resistor, shunt SCR, passive filter, and (of course) the power supply. Reference the diagram below to see the layout of the circuit.

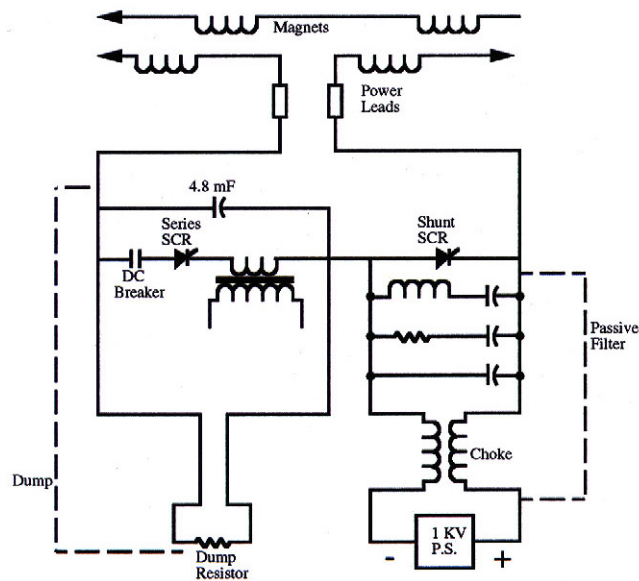


Figure 3.5 Power supply circuit.

There are four modes of operation for the TeV PS circuit.

- 1.) The PS is providing current to the bus.
- 2.) The dump resistor is dissipating current from the bus.
- 3.) The PS is not required due to the TeV being at flattop.
- 4.) Current is being dissipated through the TeV bus.

When the power supply is providing current to the TeV bus the DC breaker is closed, the series SCR is conducting, and the shunt SCR is open. This configuration allows the current that comes through the power leads, up from the tunnel, to bypass the $0.25\ \Omega$ dump resistor, enter the passive filter network and PS, and then back to the magnets. You may ask “But what about the 4.8 mF capacitor in parallel with the series SCR and DC breaker?” Not to worry. When the series SCR is conducting the capacitor is seen as an open circuit.

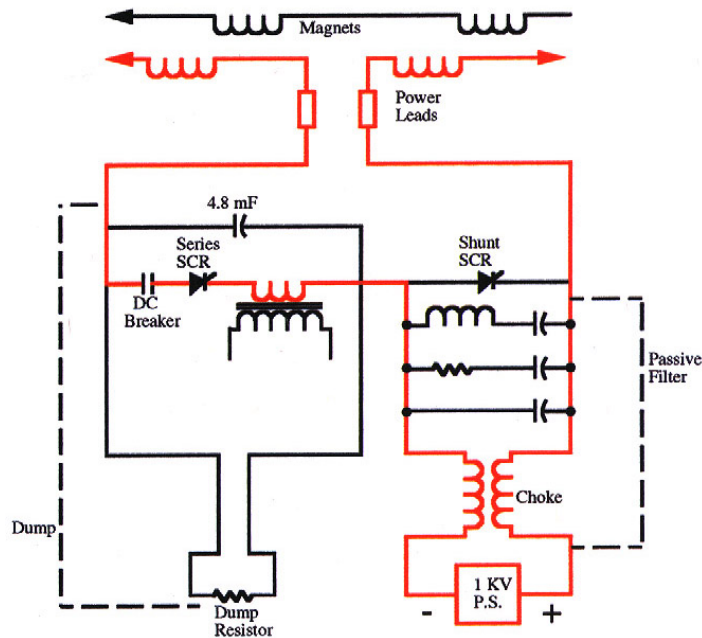


Figure 3.6 Power supply circuit showing current path during ramping.

In the case that we quench or have to dump the current in the TeV, the dump resistor will need to be brought into the circuit. This is done by commutating the series SCR, so that it does not conduct, and gating the shunt SCR, so that it does conduct. The DC breaker is opened as a backup to firing the series SCR. A 4.8 mF capacitor is added so that there is an RC circuit, which allows for a soft dump of the current. In order to open the series SCR a 1900 μF capacitor is discharged through the commutating transformer and the resulting current flow through the SCR goes to zero, which turns off the SCR.

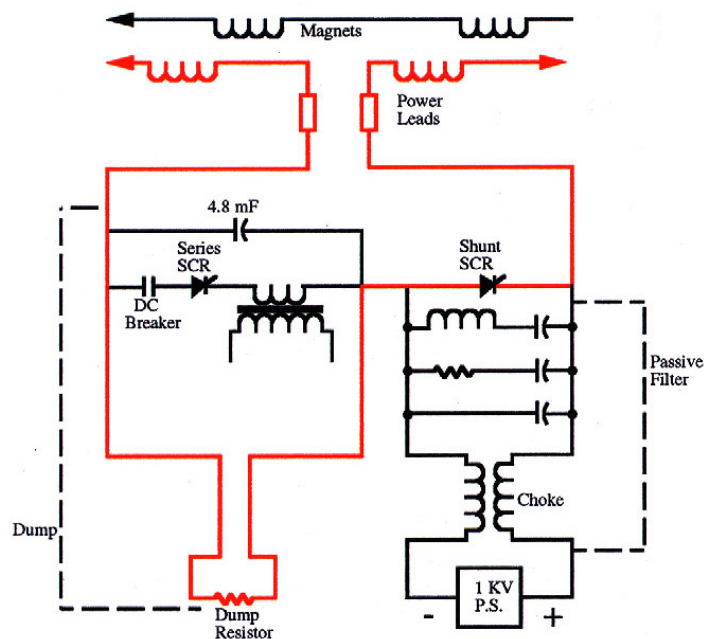


Figure 3.7 Power supply in dump mode.

Another mode the SCRs can be in is where both the series and shunt SCRs are on. This occurs when the power supply is not required due to the Tevatron being at a flattop. At this point only the regulating power supply, located at A2, provides current to the bus

since the voltage required is small. At flattop or during any constant energy segment of the ramp the regulator is the only power supply on.

When the bypass is fired all of the series and shunt SCRs around the ring are gated on, making them conduct. The current in the Tevatron then bleeds away due to the resistive warm bus segments around the ring, usually in the zero locations and PS locations.



Figure 3.8 The top picture shows the disconnect, VCB, and transformer outside of the service building. The left figure is the power supply with the choke next to it. The above picture is that of the dump/filter cabinet.

TECAR

A brief description of TECAR (Tevatron Excitation, Controller And Regulator) was given earlier in this chapter. Now a full explanation of this processor's responsibility will be given. This microprocessor controls the ramp waveforms of the main dipoles and quadrupoles and supervises the de-excitation of the power supplies during a quench. The VME crate that houses the TECAR associated electronics is found in the A2 service building electronics room.

During ramping or excitation, TECAR is responsible for the generation of the current waveform and developing the voltage waveforms for all the power supplies. The process for each supply playing out a waveform is achieved by TECAR providing the appropriate firing angles to the SCRs. Once flattop is achieved TECAR phases out the ramping supplies, except for the regulator, by gating the shunt SCRs.

In the event of a quench or some other fault, the microprocessor takes control of shutting down the power supplies and gathers diagnostic data. When a quench protection monitor (QPM) microprocessor communicates to TECAR that a quench has occurred, TECAR, via the other QPMs, performs a ring wide shutdown of the power supplies, activates the dump switches, and triggers the quench bypass switch (QBS) controllers.

A fiberoptic link that connects TECAR with all the QPMs and a redundant hardware loop allows for continual cross checking of the current in all the power supplies and its derivatives, along with resistance measurements. TECAR broadcasts two 100 kHz pulse trains, one positive and the other negative, on the hardware loop and can inhibit either one or both of the pulses. The effect of inhibiting the pulses will cause the power supplies to turn off, and the dump switches to open. If any QPM loses communication with TECAR, the QPM will clamp both pulses.

Quench Protection System

Before discussing the quench protection system we must understand the dynamics of a quench and why it occurs. For any given superconductor there is a mathematical surface defined by temperature, magnetic field, and current density that marks a boundary between the superconducting and normal regime (Refer to figure 2.1). Tevatron magnets operate close to this boundary because cost constraints minimized the amount of superconductor to be used. The superconductor in the Tevatron was specified to have a J_c of 1800 A/mm at 5 T and 4.2K for the individual strands.

The transition from the superconducting state to the normal state can occur from the temperature in the conductor going beyond the critical temperature ($T > T_c$), for instance, due to beam loss. Another cause could be that the current or field is increased beyond the critical values. This is the beginning of a quench.

Once a normal resistive zone has formed it will propagate outward at a velocity that is dependent upon the current and field. A quench in a Tevatron magnet will expand with a velocity of

$$v = 0.36 I^2 (1 + 0.077 B^2)$$

where the velocity is in units of meters per second, I is the current in kA, and B is the magnetic field in Tesla. The above formula is applicable from a current of 1 kA to 4 kA.

About 10% of the superconducting cable is open area between the strands, which is filled with liquid helium. When a quench propagates through a magnet the helium in the normal zone vaporizes and in turn the expanding gas displaces the liquid. The current transfers from the NbTi to the copper within the strands. If the cable reaches 460 K the numerous solder splices and silver-tin coating on the strands will begin to melt. At 4400 A there is less than ½ second for removing the magnet current and preventing permanent damage.

The quench protection system protects the main bend and quadrupole magnets from the 350 MJ of stored energy in the ring should any portion of the superconductor become resistive. The major component of the quench protection system is the Quench Protection Monitor (QPM), which is responsible for monitoring the voltages across the half-cells of a given house. It determines whether a quench is occurring and, if so, fires the appropriate Heater Firing Units (HFUs) so that the magnet string becomes fully and uniformly resistive. Also, the QPM must communicate to TECAR that a quench has occurred, which in turn, through the other QPMs around the ring, turns off the power supplies, activates the dump switches, and triggers the QBS controllers. The refrigerator microprocessor receives the appropriate information from the QPM as to which cells have quenched so that the cool-down can begin immediately.

The half-cell voltage monitoring is accomplished by using Voltage-to-Frequency Converters (VFCs). The cables from the converters to the magnets in the tunnel are ~200 m long and any given cable serves as the positive input for one VFC and the negative input for the adjacent VFC. The VFC output is read by the QPM scalars, which are auto-zeroed periodically from the MCR to remove any voltage drift over time.

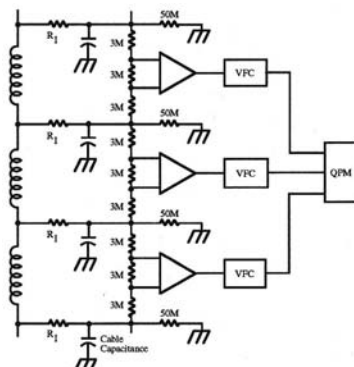


Figure 3.9 VFC connections to each half cell.

The detection of a quench is based upon the difference between the measured half-cell voltage and the expected inductive voltage. The cell voltage can be written as

$$V_{\text{cell}} = -L \, dI/dt + V_{\text{resistive}}$$

where L is the inductance of the half-cell and $V_{\text{resistive}}$ is, hopefully, zero during normal operation. With the resistive voltage at zero the cell voltage is purely inductive. The above equation can be rewritten as

$$V_{\text{resistive}} = V_{\text{cell}} + L \, dI/dt$$

The polarity of a VFC measurement is negative so that when V_{cell} is fully inductive $V_{\text{resistive}}$ will be zero. During a quench the cell voltage becomes more negative and thus the resistive voltage becomes a negative value. The threshold limit is -0.5 V before the QPM detects a quench. Also a possibility is a malfunction, where a VFC card fails and $V_{\text{resistive}}$ rises above 3.0 V. The QPM proceeds as if this were an actual quench. Since $V_{\text{resistive}}$ is of opposite polarity to the actual quench, this event is called an antiquench.

The VFCs are located under the QPM in the Tevatron service building electronics rooms. There are three types of VFCs: 1) 10 V, 2) 200 mV, and 3) 200 V. The 200 Volt VFCs are used for measuring the resistive voltage across the half cell. The 200 mV VFCs are connected to the power leads and the 10 V VFCs are used for voltage to ground measurement on the bus.

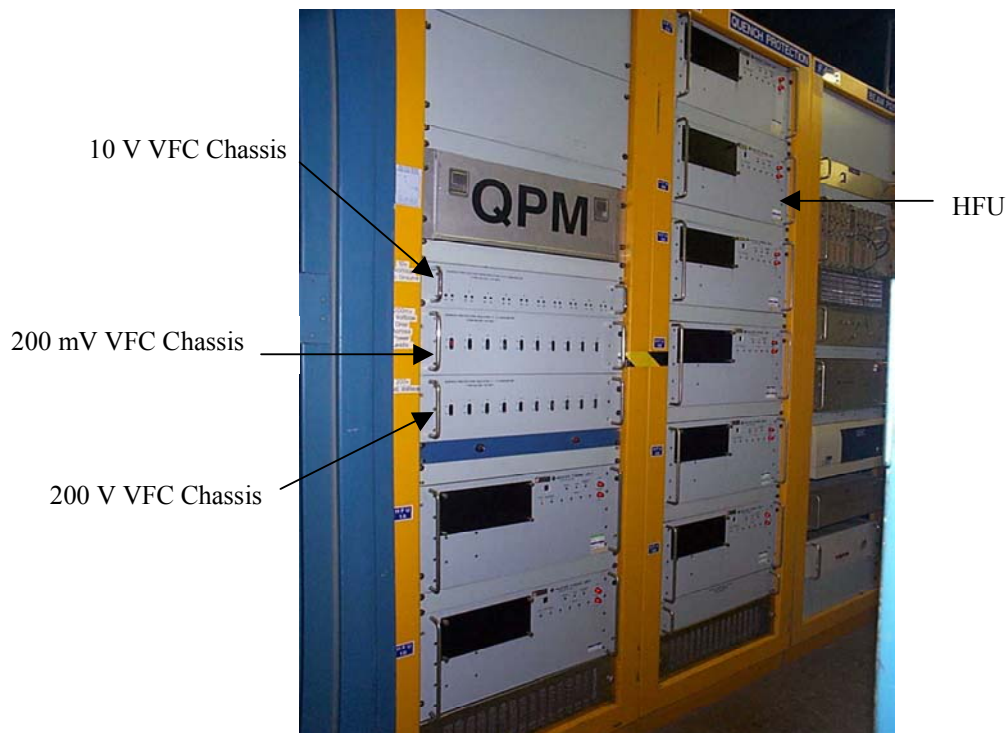


Figure 3.10 QPM and HFU racks located in an electronics room.

The HFUs contain capacitors that remain charged until a quench is detected within their cell. When fired by a command from the QPM, each HFU deposits 650 J of energy into the heater strip located between the superconductor and coil collar in the magnet. Testing the discharge time constants of the capacitors is a procedure performed in the MCR, which ensures that sufficient energy is being deposited into the magnets. When the HFU energy is dumped into the dipole heaters it causes a uniform voltage distribution throughout the magnet.

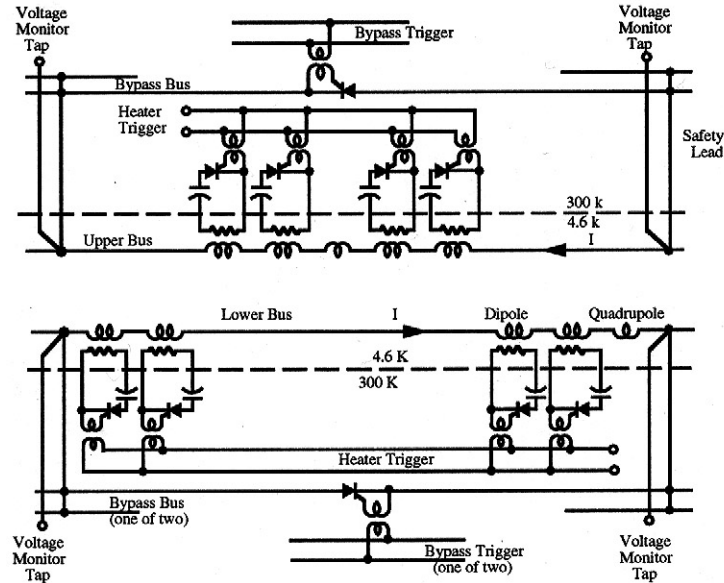


Figure 3.11 Cell schematic showing an HFU circuit, voltage tap connections for VFCs, and the quench bypass system.

The quench bypass circuits consist of two independently controlled thyristors (A and B) and a self-firing circuit that will turn on the QBS once the voltage across the cell reaches 200 V. They are connected to the magnets via the safety leads. The QBSs are semiconductors and sensitive to radiation so holes have been bored into the Tevatron tunnel and the QBS placed within for shielding.

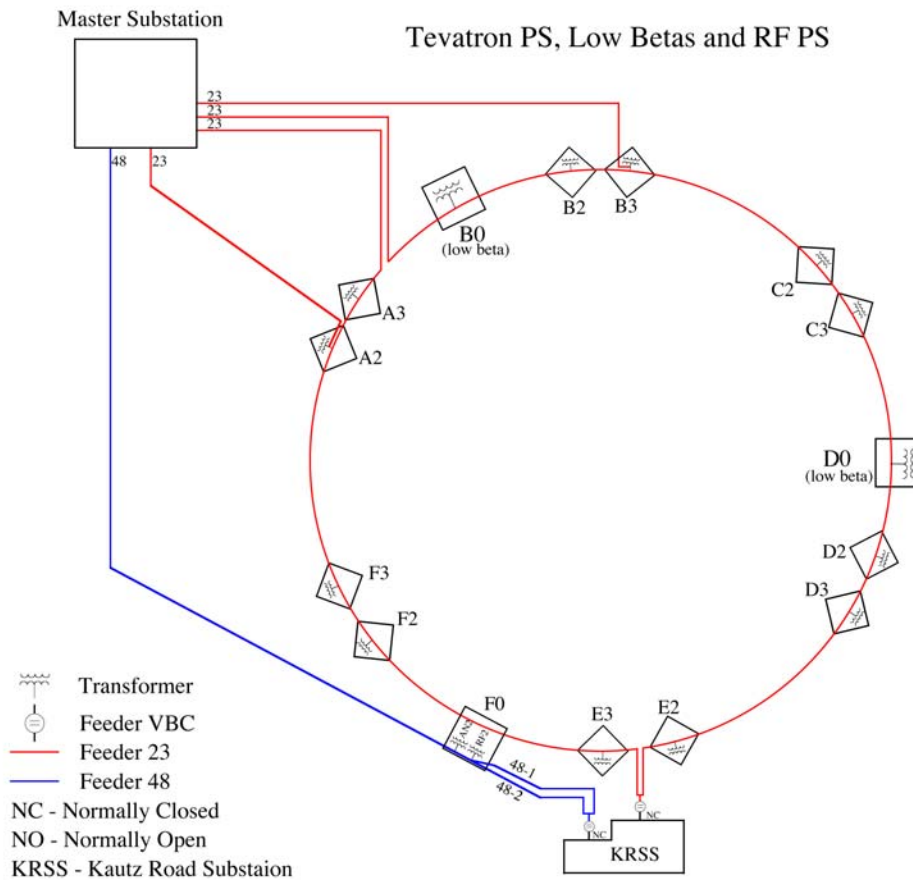


Figure 3.13 Pulsed power distribution for the 2 and 3 service buildings, low β power supplies, and RF systems.

Feeder 45 provides conventional power to all service buildings including zero buildings, and E4R. Conventional refers to the power for lighting, relay racks, and air conditioning. Critical systems, like the QPMs, CVTs, fire detection, etc., are each on an uninterruptable power supply or battery backup. At F0, this feeder provides all of the power to the RF systems except for the anode power supply and the water heaters. Feeder 45 also has the capability of being backfed from KRSS. The anode power supply and the water heaters for the TeV RF are on Feeder 48. The normal source of power for this feeder is MSS and the backfeed is KRSS.

CDF collision hall, D0 collision hall, and the C4 pump house power are fed from Feeder 49. MSS provides the power to the feeder and it can be backfed from Feeder 45.

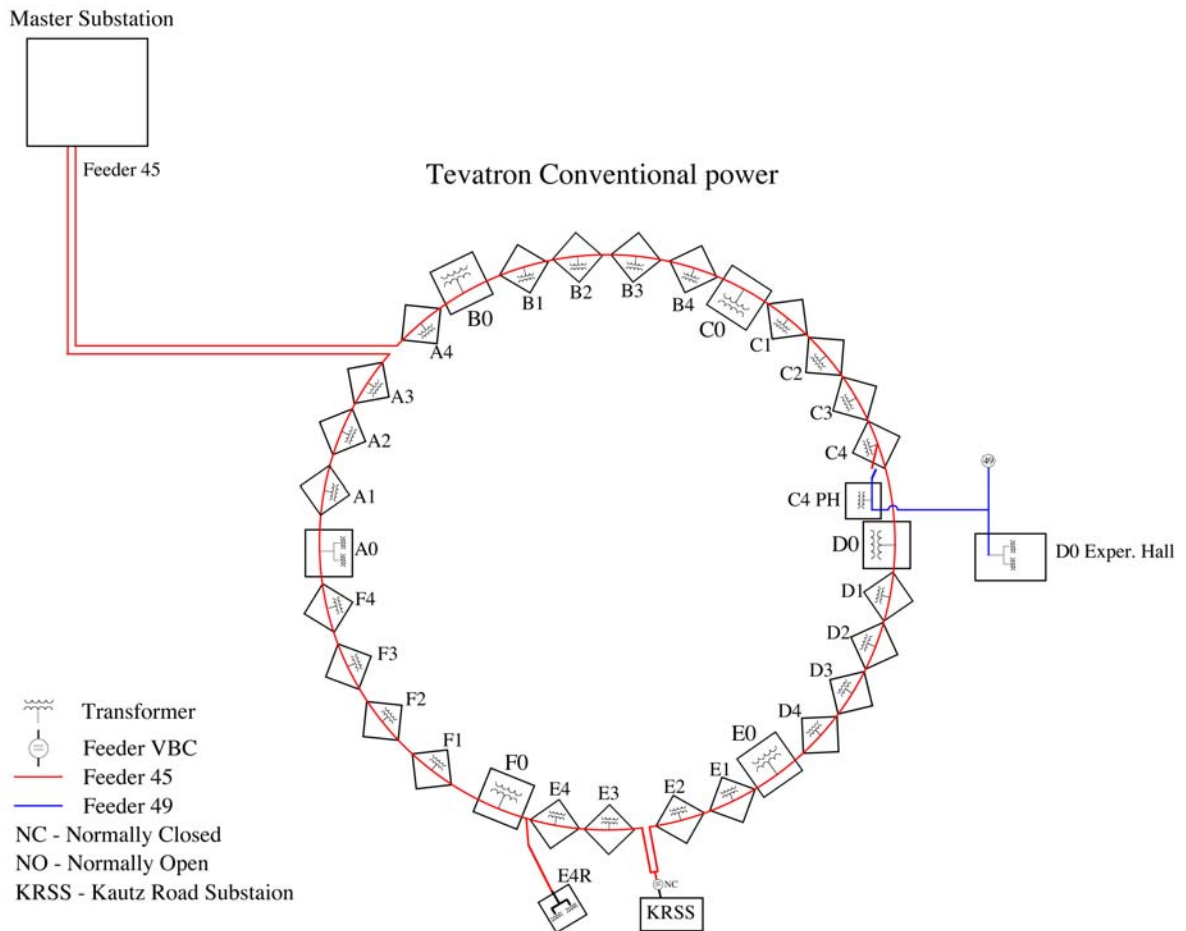


Figure 3.14 Conventional power distribution for service buildings and collision halls.

The Mycom compressors at each of the zero buildings used for maintaining helium pressures in the discharge and suction lines are on two separate feeders, 46A and 46B. Feeder 46A provides power to A0, C0, E0, and EA compressors. This circuit is fed from MSS and can be backfed from KRSS. Feeder 46B, which powers B0, BA, D0, DA, and F0, is fed from KRSS and backfed from MSS. Placing the feeders at separate substations was done so that if one feeder goes down the entire helium inventory would not be lost. Compressors from one feeder can partially maintain the pressure distribution around the ring.

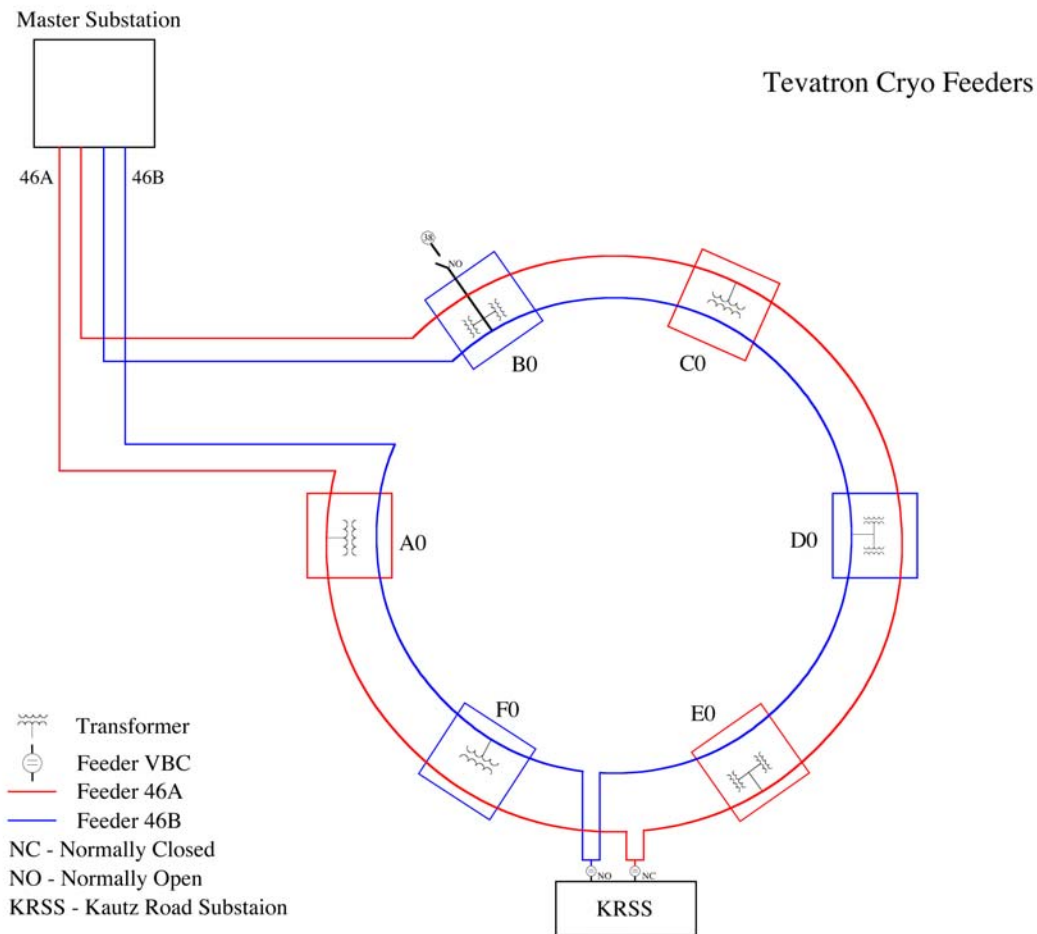


Figure 3.15 Cryogenic compressor feeder distribution.

LCW

The heat exchange system at each service building serves to cool Tevatron correction element power supplies, the warm bus, and the main power supplies. From F1 to F4, also known as the Main Ring Remnant, the heat exchange system provides additional cooling to remnant magnets, their power supplies, and the associated correction element power supplies. To accomplish all of this, the LCW heat exchanges with pond water in heat exchangers located at each service building.

The pond pumps are located in the cement pit on the pond side of Ring road. These are used to circulate pond water, at a regulated flow, between the heat exchangers in the service buildings and the ponds outside. By diverting a portion of regulated LCW through the heat exchanger and mixing it back into the regular LCW flow, the desired temperature for the LCW is reached.

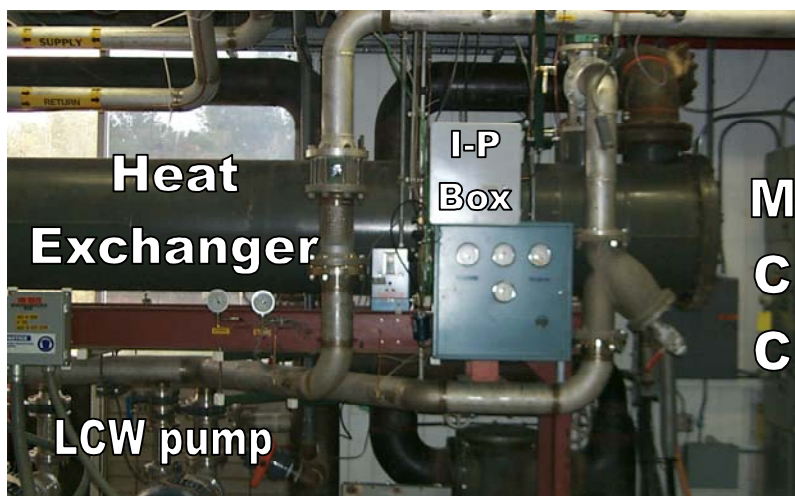


Figure 3.16 LCW Equipment in a service building.

LCW pumps are used to circulate the LCW through the heat exchangers, and out to the various heat loads. The flow of LCW around the ring is accomplished by the service building LCW pumps alone. Although the system is designed to be self-sufficient, one should still be aware that when a pump trips off it puts a burden on the two adjacent houses. The long straight sections have additional water requirements due to extra magnets in the tunnel and power supplies in the zero service buildings. Cooling problems can arise if an LCW pump is off at either the 1 or 4 building adjacent to the zero building. If necessary the pond and LCW pumps can be run in local (or hand) at the Motor Control Center (MCC) at each house. These wall breakers are located opposite the service building door, behind the heat exchanger.

To maintain some form of consistency in the operating characteristics of the magnets and other heat loads, the supply temperature of the LCW is regulated between 90 degrees F to 100 degrees F, depending on the ring wide heat load. The Love 2600 controller regulates the temperature at the 1 and 4 buildings, with the 3 buildings serving as a back up. There is no regulation at the 2 buildings. The Love 2600 controller operates the LCW valve on top of the heat exchanger. So where's the Love. The electronics reside in a chassis mounted in the 3 bay rack, opposite the electronics room.



Figure 3.17 Love 2600 Controller

The controller operates a Current-to-Pressure transducer, which is supplied 20 psi air from the air compressor adjacent to the heat exchanger. The I-P converts the 4-20 mA control signal sent by the Love controller into a 3-15 psi signal received by the pneumatic valve positioner/actuator (3=valve closed, no cooling; 15=valve full open, maximum cooling). A gray box in front of the heat exchanger contains the I-P. The key to access the I-P box is located in the Crew Chief's cabinet.

Under normal operation, all Love controllers are configured to operate off a remote set point. This set point can be modified via ACNET consoles. If the set point falls out of an acceptable range (65-115 degrees F), the controller will revert to its local set point. When the remote set point regains to an acceptable level the controller will again operate based on the remote set point.

The TeV LCW temperature control system also allows for local control of the valve in case of temperature regulation problems. There are 3 approaches one may take to valve manipulation; 1. adjusting the local set point, 2. manually setting the valve position with the Love Controller, or 3. bypassing the Love Controller/I-P entirely and manually controlling the amount of air to send to the valve.

Local Adjustment of the set point is accomplished by pressing the index key on the Love Controller, using the up or down arrows to change the set point, and pressing enter to lock it in.

The manual valve position control options are more crude ways of controlling the temperature, because the temperature regulation is completely bypassed, and no compensation for pond water temperature will be done, except for manual intervention.

Manually setting the valve position with the controller is accomplished by pressing the Auto/Manual Key on the Love Controller until the "MAN" lights up, using the up or down arrows to change the percentage of controller output (MAX = 20 mA), and pressing enter to lock it in.

To bypass the Love Controller/I-P, close the LCW valve using the MANUAL mode of the Love Controller if possible. Otherwise, turn the gradual switch all the way to the left (counterclockwise) before closing valves C and D and opening valves B and A.

Turning the gradual switch clockwise opens the LCW valve to the heat exchanger and provides more cooling. Once a manual valve position is selected using the gradual switch, the valve will not move if the system is undisturbed.

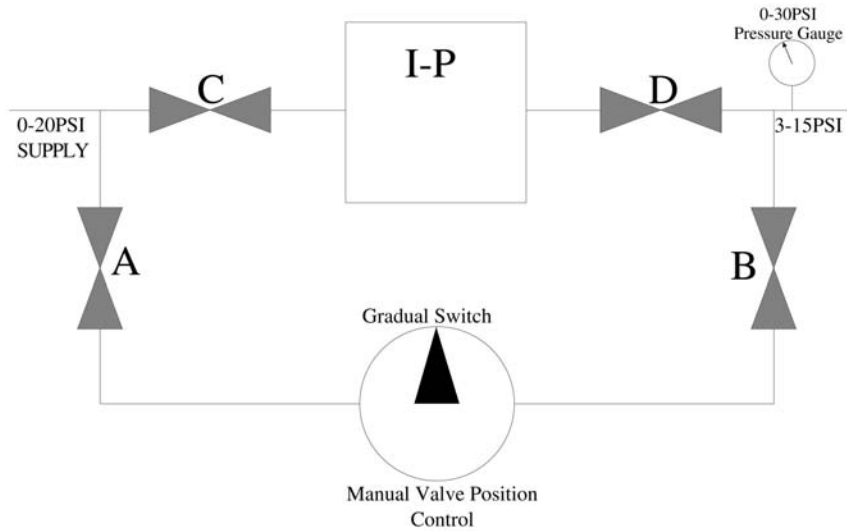


Figure 3.18 Manual override schematic.

In the service building, the analog temperature gauges are mounted on the pipe near the enclosure door. In addition, the supply temperature is displayed on the top readout of the Love Controller. In the A-E sector #2 and 3 buildings, the pressure gauges are located behind the 3 Bay Rack. In all other buildings, the pressure gauges are located on the heat exchanger frame, above the pumps. In buildings with running pumps, the nominal supply pressure is about 180 psi and return pressure is around 30 psi with an average flow of 300 gpm.

